Supplementary Material for paper "Measuring incompatible observables by exploiting sequential weak values": experimental details

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The setup realised for our experiment is presented in Fig. 1: it hosts a heralded single-photon source based on pulsed parametric down-conversion (PDC), exploiting a 796 nm mode-locked Ti:Sapphire laser (repetition rate: 76 MHz) whose second harmonic emission pumps a $10 \times 10 \times 5$ mm $LiIO_3$ nonlinear crystal, producing Type-I PDC.

The idler photon ($\lambda_i = 920$ nm) is coupled to a single-mode fiber (SMF) and then addressed to a Silicon Single-Photon Avalanche Detector (SPAD), heralding the presence of the correlated signal photon ($\lambda_s = 702$ nm) that, after being SMF-coupled, is sent to a launcher and then to the free-space optical path, where the experiment for weak values evaluation is performed. We have estimated the quality of our single-photon emission obtaining a $g^{(2)}$ value (or more properly a parameter α value [1]) of (0.13 ± 0.01) without any background/dark-count subtraction.

After the launcher, the heralded single photon state is collimated by a telescopic system, and then prepared (pre-selected) in a linear polarization state $|\psi_i\rangle$ (by means of a calcite polarizer followed by a half-wave plate). The first weak interaction is carried out by a 2 mm long birefringent crystal (BC_V), whose extraordinary (e) optical axis lies in the Y-Z plane with an angle of $\pi/4$ with respect to the Z direction. Due to the spatial walk-off effect experienced by the vertically-polarized photons (i.e. along Y direction), horizontal- and vertical-polarization paths get slightly separated along the Y direction, inducing in the initial state $|\psi_i\rangle$ a small decoherence leaving it substantially unaffected. In our experimental conditions, i.e. $g/\sigma \sim 0.15$, being the "decoherence" coefficient on the off-diagonal elements $\kappa_D = \exp[-g^2/(2\sigma)^2]$, we expect $\kappa_D \sim 0.982$; this is confirmed by the experimental tomographic reconstruction of the state, giving a fidelity $F = 0.997$ with respect to the theoretical predictions.

Together with the spatial walk-off, the birefringent crystal also induces on this single-photon state a temporal walk-off and eventually a polarization change, both to be eliminated in order to avoid unwanted additional decoherence effects. We were able to nullify this unwanted effects by adding another birefringent crystal of properly chosen length (1.1 mm) with the optical axis lying on the X direction, in order to compensate the temporal walk-off without introducing any additional spatial walk-off. This second crystal is mounted on a piezo-controlled rotator (having a nominal resolution $0.001°$) allowing almost perfect temporal compensation, i.e. to avoid any unwanted circularity in the polarisation state coming from the previous interaction.

After this, the photon goes to the second weak interaction module. It is constituted by a system (BC_H) of two birefringent crystals rotated by $90°$ with respect to the previous one, i.e. the first crystal has its optical axis in the X-Z plane, while the second one has the optical axis in the Y direction, inserted between two half-wave plates. By rotating both wave plates of the same angle with respect to the H-axis, one obtains the weak interaction on the linear polarisation state $|\psi\rangle$ with the polarisations separation appearing along the X direction. This can be thought of as a simple example of the unitary evolution between weak interactions affecting the sequential weak value, as discussed in [2].

After both WMs are performed, the photon meets a half-wave plate and a calcite polarizer, projecting the state onto the post-selected state $|\psi_f\rangle$, and then it is detected by a spatial-resolving single-photon detector prototype. This device is a two-dimensional array made of 32×32 "smart pixels" -each pixel includes a SPAD and its front-end electronics for counting and timing single photons [3]. All the pixels operate in parallel with a global shutter readout. The SPAD array is gated with 6 ns integration windows, triggered by the SPAD on the heralding arm. Being the heralding detection rate in the order of 100 kHz, the effective dark count rate of the array is drastically reduced by the low duty cycle, improving the signal-to-noise ratio.

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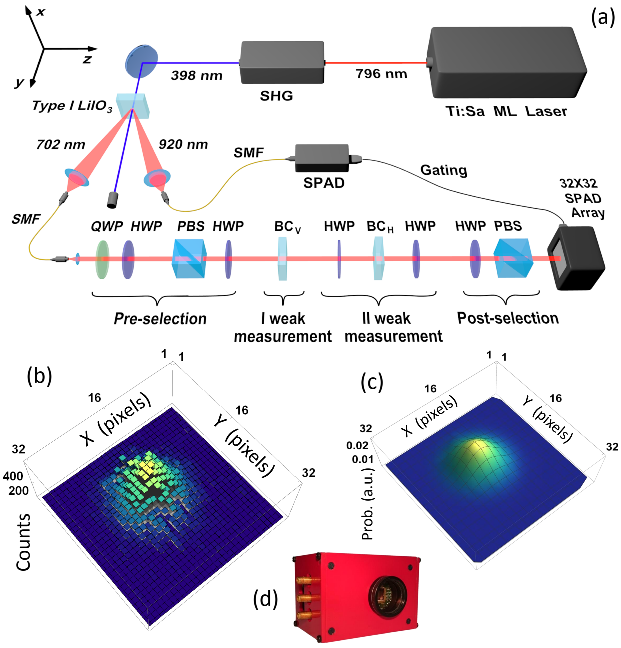

FIG. 1: (a) Experimental setup and detection apparatus. (a) A frequency doubled mode-locked Ti:Sa laser pumps a $LiIO_3$ Type-I PDC crystal. The idler photon ($\lambda_i = 920$ nm) is coupled to a single-mode fiber (SMF) and addressed to a SPAD heralding the correlated signal photon ($\lambda_s = 702$ nm) that is prepared in a linear polarization state (pre-selection block) and sent to the in-air weak interaction apparatus. The first weak interaction is operated by the BC_V system (composed of two orthogonal birefringent crystals, the first one realizing the weak interaction, the second one compensating temporal walk-off and decoherence effects), followed by the BC_H block (identical to BC_V but with a 90° rotation of the Z axis), in which the second weak interaction takes place. Just before and after BC_H, two half-wave plates are put in order to arbitrarily change the basis of this second measurement. Finally, the photon is post-selected and detected (SHG: Second Harmonic Generator; QWP: Quarter Wave Plate; HWP: Half Wave Plate; PBS: Polarizing Beam Splitter; BC: Birefringent Crystal). (b) Typical single data acquisition obtained with our spatial resolving single-photon detector (32×32 SPAD camera), after noise subtraction. It represents the number of counts acquired in 300 s versus the different pixels of the SPAD array. (c) The corresponding predicted probability distribution calculated according to the theory. (d) Our SPAD camera prototype.

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